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APPLICATION FOR LETTERS PATENT
OF THE UNITED STATES

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TITLE OF INVENTION:

METHOD AND APPARATUS FOR PROVIDING PREDICTIVE MAINTENANCE OF A DEVICE BY USING MARKOV TRANSITION PROBABILITIES

TO WHOM IT MAY CONCERN, THE FOLLOWING IS
A SPECIFICATION OF THE AFORESAID INVENTION

METHOD AND APPARATUS FOR PROVIDING PREDICTIVE MAINTENANCE OF A DEVICE BY USING MARKOV TRANSITION PROBABILITIES

Reference is hereby made to copending:

U.S. Provisional Patent Application No. 60/255,615 filed 12/14/2000 for NEURAL NETWORK-BASED VIRTUAL AGE ESTIMIATION FOR REMAINING LIFETIME, in the names of Christian Darken and Markus Loecher, Attorney Docket No. 00P9072US;

U.S. Provisional Patent Application No. 60/255,614 filed 12/14/2000 for POLYNOMIAL BASED VIRTUAL AGE ESTIIMATION FOR REMAINING LIFETIME PREDICTION, in the names of Markus Loecher and Christian Darken, Attorney Docket No. 00P9073US; and

U.S. Provisional Patent Application No. 60/255,613 filed 12/14/2000 for MARKOV TRANSITION PROBABILITIES FOR PREDICTIVE MAINTENANCE, in the name of Markus Loecher, Attorney Docket No. 00P9074US,

of which priority is claimed and whereof the disclosures are hereby incorporated herein by reference.

Reference is also made to copending patent applications being filed on even date herewith:

METHOD AND APPARATUS FOR PROVIDING A VIRTUAL AGE ESTIMATION FOR REMAINING LIFETIME PREDICTION OF A SYSTEM USING NEURAL NETWORKS, in the names of Christian Darken and Markus Loecher, Attorney Docket No. 00P9072US01; and METHOD AND APPARATUS FOR PROVIDING A POLYNOMIAL BASED VIRTUAL AGE ESTIMATION FOR REMAINING LIFETIME PREDICTION OF A SYSTEM, in the names of Markus Loecher and

Christian Darken, Attorney Docket No. 00P9073US01, and whereof the disclosures are hereby incorporated herein by reference.

The present invention relates generally to the field of failure prediction and, more specifically to providing advance warning of impending failure for a variety of systems and devices, terms used herein interchangeably.

Devices and apparatus used in various fields of medicine, industry, transportation, communications, and so forth, typically have a certain useful or operational life, after which replacement, repair, or maintenance is needed. Generally, the expected length of the operational life is known only approximately and, not untypically, premature failure is a possibility. Simple running time criteria are typically inadequate to provide timely indication of an incipient failure. In some applications, unanticipated failure of devices constitutes a at least a nuisance; however, more typically, unanticipated device failure may be a major nuisance leading to costly interruption of services and production. In other cases, such unexpected failure can seriously compromise safety and may result in potentially dangerous and life-threatening situations.

In accordance with an aspect of the invention, systems and/or devices are classified into "healthy" states and conditions which signal imminent malfunction is accomplished through computation of transition probabilities of selected variables.

In accordance with an aspect of the invention, a method for providing predictive maintenance of a device, comprises the steps of modeling as a time series of a discretely sampled signal representative of occurrences of a defined event in the operation of the device, the time series being modeled as two-state first order Markov processes with associated transition probabilities, wherein one state applies when the number of the occurrences exceeds a certain threshold, and the other state applies when the number of the occurrences falls below the certain threshold; computing the four transition probabilities the last N states S_n, where N is a predetermined number, conducting a supervised training session utilizing a set of J devices, which have failed due to known causes and considering the two independent probabilities and, the training session

comprising computing the two-dimensional feature vectors for the initial *M* windows of *N* scans, computing the two-dimensional feature vectors for the final *N* number of scans, plotting a scatter-diagram of all 2D feature vectors, and deriving a pattern classifier by estimating the optimal linear discriminant which separates the two foregoing sets of vectors; and then applying the classifier to monitor the persistence of occurrences of the defined event in the operation of the device.

The method and apparatus will be more fully understood from the following detailed description of preferred embodiments, in conjunction with the Drawing in which

Figure 1 (SOLE FIGURE) shows a block diagram for apparatus in accordance with the principles of the invention.

Figure 1 shows a computer 20 equipped with data and program storage equipment 22 and a source 26 of programs for training and operating in an interactive manner as hereinafter described. Data from training sessions as further explained below is provided at 24. A device or system 28 which is being monitored provides data by way of data collection interface unit 30 to computer 20. Computer 20 provides an imminent or prospective alarm as to lifetime expiration and/or failure expectation at an alarm device 32.

An important exemplary application of principles of the present invention relates to predicting failure of X-ray tubes. Arcing is known to occur in X-ray tubes. In the case of X-ray tubes, the frequency of occurrence of high-voltage (HV) arcs is chosen as the main input to the algorithm in the present exemplary embodiment. HV-arcing is characterized by a lightning-like discharge and a temporary voltage breakdown inside vacuum-insulated high-voltage devices. Typically, it is a frequently occurring but usually short-lived malfunction in such devices.

The method in accordance with the present invention is widely applicable in many fields. In order to facilitate understanding of the invention and to illustrate the use of device-specific information and parameters, the invention will next be more fully described by way of an exemplary, non-limiting embodiment relating to X-ray tubes; where appropriate, generally applicable notions are also stated in the context of the specific

exemplary embodiment. The example used is also appropriate in that an unexpected failure of such an X-ray tube, for example during a critical surgical procedure, should be avoided insofar as is possible.

Suppose x_n ($n = 1 \ldots N$) represents the time series of a discretely sampled signal which for the sake of clarity is assumed in the present embodiment to be the number of high-voltage arcs measured during the active phase of an X-ray tube. Furthermore, it is assumed that the X-ray tubes are operated in a non-continuous manner, which is characteristic for a clinical environment where discrete, consecutive "scans" represent its main usage.

The physical causes for HV-arcs primarily fall into three classes: (i) leaks in the casing, which lead to a reduced vacuum, (ii) microscopic particles, which are usually destroyed by the arcing, and (iii) sharp protrusions on the surface of the anode or cathode. Arcing due to leaks marks the irreversible decay of a tube's proper functioning. On the contrary, the latter two disruptions are transitory and reversible. In fact, in cases (ii) and (iii) arcing (a symptom) serves to eradicate its own cause by destroying the particles or protrusions.

Consistent with this physical picture, the time-series x_n shows noticeable persistence and cannot be modeled by e.g. a Poisson process. Removal of particulates requires a sufficient number of consecutive HV-arcs, which manifests itself as strong temporal correlations within x_n. The fundamental problem is to decide, based solely upon a finite history of arcing, whether the tube is about to irreversibly fail or whether the malfunctioning can be considered transitory.

In accordance with an aspect of the invention, the timeseries x_n is modeled as two-state first order Markov processes with associated transition probabilities $p(i|j)$. State 1 is assumed if the number of arcs exceeds a certain threshold T, state 0 if it falls below the same number:

$$S_n = \begin{cases} 0 & if \quad x_n \leq T \\ 1 & if \quad x_n > T \end{cases}$$

We typically take T to be zero. Assuming x_n to result from an underlying 1st order Markov processes implies stochastic switching between the two states. The transition probability $p(i|j)$ is the switching probability from state j to state i. More accurately, it is the probability that $S_n = i$ given that $S_{n-1} = j$. These four transition probabilities are computed over the last N states S_n, where N typically is of the order of a few hundred scans. Note that the transition probabilities of a k^{th} order Markov process would depend on the last k states: $p(S_n) = p(S_n \mid S_{n-1,\ldots,} S_{n-k})$.

We simplify the classification problem by only considering the two probabilities $p(1|1)$ and $p(1|0)$. Note that the two remaining probabilities are not independent: $p(0|1) = 1 - p(1|1)$ *and* $p(0|0) = 1 - p(1|0)$). Utilizing a set of J tubes, which have failed due to known causes, the supervised training strategy in accordance with the principles of the invention is as follows:

- Compute the two-dimensional feature vectors $f_i = \{p(1|1), p(1|0)\}_i$ for the initial M windows of N scans.
- Compute the two-dimensional feature vectors $f_f = \{p(1|1), p(1|0)_f$ for the final N number of scans.
- Plot a scatter-diagram of all 2D feature vectors $(f_i)_n$ and $(f_f)_n$, $(n = 1 \ldots J)$.
- Now the problem is reduced to a classic pattern classifier: Estimate the optimal linear discriminant, which separates the two sets of vectors.
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The classifier thereby obtained is applied to monitor the persistence of arcing in operating tubes. At each scan the transition probabilities are updated and the feature vector $f = \{p(1|1), p(1|0)\}$ constructed. If f falls into the "bad" region of the classifier, the tube is deemed close to the end of its useful life and advance warning of imminent failure is given.

It will be understood that the invention may be implemented in a number of ways, utilizing available hardware and software technologies. Implementation by way of a

programmable digital computer is suitable, with or without the addition of supplemental apparatus. A dedicated system may also be used, with a dedicated programmed computer and appropriate peripheral equipment. When various functions and subfunctions are implemented in software, subsequent changes and improvements to the operation are readily implemented.

While the present invention has been described by way of illustrative embodiments, it will be understood by one of skill in the art to which it pertains that various changes and modifications may be made without departing from the spirit of the invention. Such changes and modifications are intended to be within the scope of the claims following.